New LCA Theses

Materials and Energy Flows in Industry and Ecosystem Networks

Sangwon Suh

Institute of Environmental Sciences (CML), Leiden University, PO Box 9518, 2300RA Leiden, The Netherlands (suh@cml.leidenuniv.nl). Currently at Carnegie Mellon University, Department of Civil and Environmental Engineering, 5000 Forbes Ave., Pittsburgh, 15213 PA, USA (suh@cml.leidenuniv.nl)

In the modelling of linear flow networks, different disciplines have developed similar methods, using similar mathematical formulations, all with matrix inversion as a basis. These include Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Input-Output Analysis (IOA) and ecological network flow analysis. By combining their adjoining and overlapping domains of application or by using the insights in one domain as inspiration and guidance in other domains, scientific improvements can be achieved and communication between closely related sciences established, to some extent even leading to combining them in hybrid analysis.

Especially in the field of LCA, there are a number of questions (see questions 1.1 and 1.2 below), which can be answered in a better way, by using insights from other domains of network flow analysis. The converse is also true, where the treatment of waste flows in IOA can be improved with insights from LCA (see question 1.3). In learning from insights in different domains of network flow analysis, the question arises as to whether there is a common architecture in these models (question 2.1) or nor, and, if this is established, how inter-system comparisons and hybridisation may give added insight (question 2.2). With mathematical tools and interpretations aligned and integrated, there are questions to solve in application, in terms of data to fill the models (question 3.1), and in terms of adherence of LCA to ISO standards which have already been set up in this field (question 3.2). Finally, an example of application as related to climate change shows how environmentally extended IOA can help basic questions as related to policy (question 3.3).

The questions indicated above have been answered in the eight chapters of this thesis. Most of the questions were discussed in more than one chapter. Here, per question, an encompassing answer is given. Finally, results are discussed in the conclusions and discussions together with on-going research and recent developments.

Theme 1. Modelling Choices in Analysing Materials and Energy Flow Networks

Question 1.1. "*How to systematically broaden the system in LCA without loss of resolution?*"

In Chapter 4, the model structure of LCA is reformulated as a functional flow-by-process framework and it is inter-connected with IOA in a single matrix. The resulting, integrated hybrid LCA model enables full feedback loops between the two systems, including inputs from the embedding economy to the detailed functional flow-based system and *vice versa*, and expands the system while preserving all detailed, process-level information. Various analytical algorithms that have been developed for LCA and IOA can be applied to the integrated hybrid model without a loss of consistency. Structural Path Analysis (SPA) is applied to the hybrid system as an example.

Using hybrid analysis, a case study showed that the cut-offs of an LCA study on a flooring material contribute 8 to 73% of the process-LCA results, depending on the impact category considered.

Question 1.2. "*What are the available approaches in LCA computation, and what can be best approaches for different types of application?*"

In Chapter V, in total, six techniques for Life Cycle Inventory (LCI) computation of a product system are distinguished. These are: computation using a process flow diagram; matrix expression of the process relations; input-output (IO) based LCI; and three different forms of hybrid analysis: the tiered hybrid analysis; the IO-based hybrid analysis; and the integrated hybrid analysis. These approaches are evaluated with regard to data requirements, uncertainty of source data, upstream system boundary, technological system boundary, geographical system boundary, available analytical algorithms for interpretation, time and labour intensity, simplicity of application, required computational tools, and available software tools. Matrix representation of a product system clearly is superior to the flow diagram method for all but the most simplified systems. Pure IO-based LCI can at best be used as a first proxy. When comparing the pure process-based LCI with the integrated hybrid analysis, the latter has a clear advantage in terms of the quality of the result, especially in terms of system completeness. However, it adds to the cost of already expensive and time-consuming full process LCA. A rational strategy at a case level could be to follow a step-wise approach. The step-wise approach can start with only a few centrally important processes worked out in detail, which is quite cheap and fast, while all background processes are covered by IOA. Then, focussed on where main contributions and uncertainties are, a stepwise build-up of resolution can follow, until a sufficient quality of result has been obtained. At all steps of development, there always is a full and consistent system definition, with resolution being added as required.

Question 1.3. "*Are there consistent approaches of treating wastes in PIOT? If so, which one is the most desirable?*"

Yes, there are. In Chapter VI, two consistent but different approaches to cope with the problem of waste in PIOT are presented, with their proofs. In approach 1, it is assumed that only the usable output of an industry is responsible for all factor inputs to the industry regardless of whether these are actually transformed into wastes or whether these go into usable products. Approach 2 assumes that the waste and the usable output of an industry are equally responsible for the factor inputs to the industry, in proportion to their mass. It should be noted that the very motivation for a productive process being operated is the economic value of its usable outputs. It is this economic motive which is causing the waste to be generated, as an unwanted side effect. So, approach 1 is argued to be more appropriate in the context of analysing economic activities.

Theme 2. A Common Architecture for Analysing Materials and Energy Flow Network

Question 2.1. "*Is there a common architecture in materials and energy flow network analysis in economics, LCA, MFA and ecology?*"

Yes, there is. In Chapter VII, a generalised framework for materials and energy flow analysis is proposed, based on the duality of

input-side balance and output-side balance. The generalised framework embraces network flow models of industry and ecology. General relationships between existing network flow analysis approaches in ecology, namely, environ analysis, total flow analysis, endogenised input approach, use of transitive closure matrices are derived by means of the generalised framework. The framework is also applicable for the network flow structures in both LCA and MFA.

Question 2.2. *"If so, can these be used to gain insights by e.g., inter-system comparisons or hybridisation?"*

One obvious advantage of having a common architecture that can be shared by network flow analyses of different disciplines is that systems with differing system definitions can be integrated wherever useful, without loss of consistency. The integrated hybrid model developed in Chapter III is possible only because the IO model and LCA model have been reformulated so as to share certain commonalities with regard to the fundamental assumptions, especially on how the information on materials and energy flows is structured in matrices.

A generalised framework also enables insights by providing a level ground for comparison. For instance, in Chapter VII, it is shown that independent proposals of network flow analysis in ecology often use Ghosh's supply-driven model, while the demand-driven model by Leontief has been the general practice in input-output economics. This fact reflects that the driving factors in an ecological system are the primary inputs from nature, while those in an economic system are the outputs to households, that is final consumption. In that sense, the demand-driven model is operated as if an economic system were free from the inputs from outside such as natural resources and solar energy. In that sense, the generalised framework opens up options for integrated economic-environmental analysis. Also, this framework is useful in translating the findings of one discipline for use in another. For instance, Odum's findings on ecosystem resilience and those on recycled flows in industrial ecology can both be better understood on the basis of the generalised framework.

Theme 3. Model Implementation

Question 3.1. *"Where are the data sources, and how to build a large scale environmental database for the use in LCA. IOA, hybrid LCA, MFA and broader industrial ecology applications?"*

In Chapter IV, the method and US data for compiling an environmental intervention-by-commodity database are presented. The resulting database contains 1170 kinds of different environmental interventions including emissions of greenhouse gases (GHGs), ozone layer depleting substances, and toxic emissions, eutrophying and acidifying substances, and the extraction of fossil fuels. The use of Supply and Use framework in deriving the intervention-by-commodity matrix, which often has been neglected, is presented as well. In Chapter II, the available IOTs and environmental data of 6 countries are reviewed, showing that data availability for environmental IOA is still limited but improving.

Question 3.2. *"Is hybrid LCA in compliance with ISO standards? If not, what would be useful amendments on current ISO standards?"*

In Chapter II, it is argued that, although current ISO standards are based on process analysis, according to clause 4.5 of ISO 14041, they do not preclude the use of an input-output model to describe a product system (or part of one). Moreover, it is shown that selecting a system boundary in compliance with ISO standards is, in fact, impossible without using the input-output model, and hybrid techniques using input-output analysis can and should therefore form a central element in an ISO-compatible method for boundary identification.

Question 3.3. *"Can moving towards a services-oriented economy cure our environmental problems, including those of climate change?"*

In Chapter VIII, the patterns of GHG emission induced through supply-chain networks in the US are analysed for 21 GHGs. Service sectors emit less than 5% of the total US GHG emission, and their average GHG emission intensity per dollar of output is less than one tenth of those of all other sectors, taking into account emissions induced through supply-chains (0.04kg CO_2 eq./$ versus 0.47kg CO_2 eq./$). However, focussing on household expenditure, services are responsible for 37.6% of the total industrial GHG emissions in the US, which is almost twice as much as for household consumption on electricity and transportation. So, a shift to service-oriented economy, under the current structure, entails a decrease in GHG emission intensity per unit of GDP, but will not automatically reduce the overall GHG emission in absolute terms.

In the chapter on Conclusions and Discussion (Chapter IX) major findings and recommendations are listed. A number of issues reflected from the 8 prior chapters, including the strengths and weaknesses of the network flow analysis, the basic concept of hybrid analysis as a general modelling strategy, and the interpretation of supply-driven model as a quantity model, are discussed. A number of on-going discussions related to the study have been presented as well.

The generalised conceptualisation that is consistent with the work of several now distinct research communities opens up new questions, crossing over the borders of these communities, which could not be readily addressed before. A few examples of such questions are:

- How are the materials and energy flows of an ecosystem structured to enable homeostasis and what does it imply for understanding the structure of an envisaged sustainable society?
- What are the differences in materials and energy cycles between industrial systems and ecosystems, why have such differences been made and what are the design principles that can be applied in industrial ecology?
- How have similar concepts in different disciplines, such as keystone species in ecology and key sector identification in IOA, been developed and applied in other disciplines and what can we learn from them?
- How can the concept of hybrid analysis be further applied in different fields beyond the realm of LCA?

High priority future research topics include: (1) the use of the general framework of network flow analysis for assessing options for applying E. Odum's theory of ecological succession also in industrial ecology and in an integrated ecology-economy model, especially focussing on the integration or hybridisation between the Ghosh's supply-driven model and Leontief's demand driven model; (2) a comparison between food web research in ecology and network flow analysis modelling in other disciplines, notably IOA; and (3) the implications of different waste treatment approaches in PIOT for decision support.